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AIRCRAFT INTERIOR NOISE REDUCTION BY ALTERNATE RESONANCE TUNING

PROGRESS REPORT FOR THE PERIOD ENDING DECEMBER, 1988

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Prepared for:

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SECTION 1. INTRODUCTION

Existing interior noise reduction techniques for aircraft fuselages perform reasonably well at higher frequencies, but are inadequate at lower frequencies, particularly with respect to the low blade passage harmonics with high forcing levels found in propeller aircraft. A method is being studied which considers aircraft fuselages lined with panels alternately tuned to frequencies above and below the frequency that must be attenuated. Adjacent panels would oscillate at equal amplitude, to give equal source strength, but with opposite phase. Provided these adjacent panels are acoustically compact, the resulting cancellation causes the interior acoustic modes to become cutoff, and therefore be non-propagating and evanescent. This interior noise reduction method, called *Alternate Resonance Tuning* (ART), is currently being investigated both theoretically and experimentally. This new concept has potential application to reducing interior noise due to the propellers in advanced turboprop aircraft as well as for existing aircraft configurations.

The ART technique is a procedure intended to reduce low frequency noise within an aircraft fuselage. A fuselage wall could be constructed of, or lined with, a series of special panels which would allow the designer to control the wave number spectrum of the wall motion, thus controlling the interior sound field. By judicious tuning of the structural response of individual panels, wavelengths in the fuselage wall can be reduced to the order of the panel size, thus causing low frequency interior acoustic modes to be cutoff provided these panels are sufficiently small. By cutting off the acoustic modes in this manner, a significant reduction of interior noise at the propeller blade passage harmonics should be achieved.

Current noise control treatments have already demonstrated that the mass and stiffness of individual fuselage panels can be altered. It seems reasonable, therefore, that panel resonant frequencies can be manipulated to achieve the ART effect. Application of this concept might involve the modification of existing structural panels or development of a new design for fuselage interior trim panels. Although complete acoustic cutoff will not be achievable in practice, an approximate cancellation should still substantially reduce the interior noise levels at the particular frequency of interest. It is important to note that the ART method utilizes the flexibility and dynamic behavior of the structure to good advantage, although these properties are not normally beneficial in noise control.

This progress report summarizes the work carried out at Duke University during the third six months of a contract supported by the Structural Acoustics Branch at NASA Langley. Considerable progress has been made both theoretically and experimentally as

described in the following sections. It is important to note that all of the work carried out so far indicates the ART concept is indeed capable of achieving a significant reduction in the sound transmission through flexible walls.

SECTION 2. THEORETICAL ANALYSIS

Model problem development and analysis continues with the Alternate Resonance Tuning concept. The various topics described below are presently at different stages of completion. These topics include the following:

-Investigation of the effectiveness of the ART concept under an external propagating pressure field associated with propeller passage by the fuselage;
-analysis of ART performance with a double panel wall mounted in a flexible frame using a new labor-saving panel analysis method;
-development of a data fitting scheme using a branch analysis acoustics approach combined with a Newton-Raphson computational method to determine values of critical parameters in the actual experimental apparatus;
-investigation of the ART effect with real panels as opposed to the spring-mass-damper systems currently used in most of the theory;
-parametric studies using standardized existing ART computer programs to further explore the method's usefulness;
-development of a new method of analysis which has broad application to panel/frame structures at relatively low frequencies and also provides a general analytical formulation for noise reduction concepts involving structural tuning.

Section 2a: External Pressure Field Modelling

Work Update:

This work involves the analysis of the effect of pressure disturbances sweeping along an ART panelled wall. Since the last progress report, portions of this analysis were refined and the governing equations were recast to allow a more straightforward computational procedure. At this point in time, the computer program is in the final debugging stages.

Section 2b: Double Panel Wall and Flexible Frame Development

Work Update:

While some initial work on a double panel wall had been completed as early as August, 1987, this model will be re-examined using the new labor-saving panel analysis method mentioned above and described below in Section 2e. The new method holds considerable promise with respect to reducing the amount of calculations necessary to derive analytically the ratio of transmitted to incident pressure through a fuselage wall model.

Section 2c: Newton-Raphson Data Fitting Technique

Work Update:

Knowledge of precise values of panel components used in the ART experiments would permit an attempt at matching experimental data with theoretical results. However, the values of panel mass, stiffness, damping ratios, apparent mass parameters, effective panel dimensions, and other nondimensionalized parameters critical to understanding ART performance have proven difficult to measure accurately experimentally. The Newton-Raphson data fitting program was conceptualized to derive these important nondimensionalized parameter values from the experimental data computationally using a multidimensional root finding approach. The program has met with limited initial success. For example, given a set of known nondimensional parameters which have been only slightly altered from their original correct values, the program will converge correctly to the original values. Modifications are currently being made to the program to allow convergence to the experimental data in the most general cases.

Section 2d: Analysis of the ART Concept Using Real Panels

Work Update:

The basic approach to using real panels was outlined in the July, 1988 progress report. However, this problem is now a candidate for analysis via the new labor-saving method described in Section 2e; furthermore, it is hoped that this new method will reduce analytic effort for the analysis of a general four panel geometry.

Section 2e: A More Efficient Analysis of the ART Concept

New Work Area:

The former method of deriving the ratio of incident to transmitted pressure through aircraft panels was outlined in the July, 1987 progress report for panels modelled as spring-mass-damper systems, and in the July, 1988 progress report for a two panel geometry where real plates replaced the spring-mass-damper simplification. Recall that this solution method basically followed the following path. A general pressure acoustic solution to the linearized 2D or 3D wave equation was derived, with appropriate boundary conditions. A general expression was then derived expressing the net force on each panel subsystem in terms of pressure modal amplitudes. The net force expression requires the evaluation of the integral of the acoustic pressure differential over the panel's area. These panel force expressions included unknown acoustic modal amplitudes from the general solution. The velocity of the panels was then expressed via mechanical impedance, which was in turn linked to the general solution via the momentum equation. Finally, the unknown acoustic modal amplitudes were obtained by repeated applications of orthogonality. An additional continuity equation completes a set of five equations; one for each panel velocity and a fifth equation for the transmitted pressure. The system of linear equations with complex coefficients was then appropriately nondimensionalized and solved numerically using standard solution techniques. The process is conceptually straightforward, but very laborious, especially for the four panel system.

A newer, more economical approach has proven initially successful and will be adopted for future work to be undertaken in the coming months. A single panel is selected as the focus for analysis. That panel is assumed to have some unknown velocity while the other three panels are locked in place. As before, the momentum equation is invoked to bridge from velocity to pressure. In this manner, an analytic expression for the force on any one panel may be determined as a result of the motion of the single moving panel. Exploitation of symmetry and superposition allow governing equations to be derived for all four panel velocities without considering the other panels in detail. A fifth continuity equation relates transmitted pressure to the four velocities. The resulting force equations are identical to the equations derived using the earlier method. The number of pages of analytical calculation to derive the governing equations is reduced by about a factor of five.

Section 2f: General Theory for Panel/Frame Enclosures

New Work Area

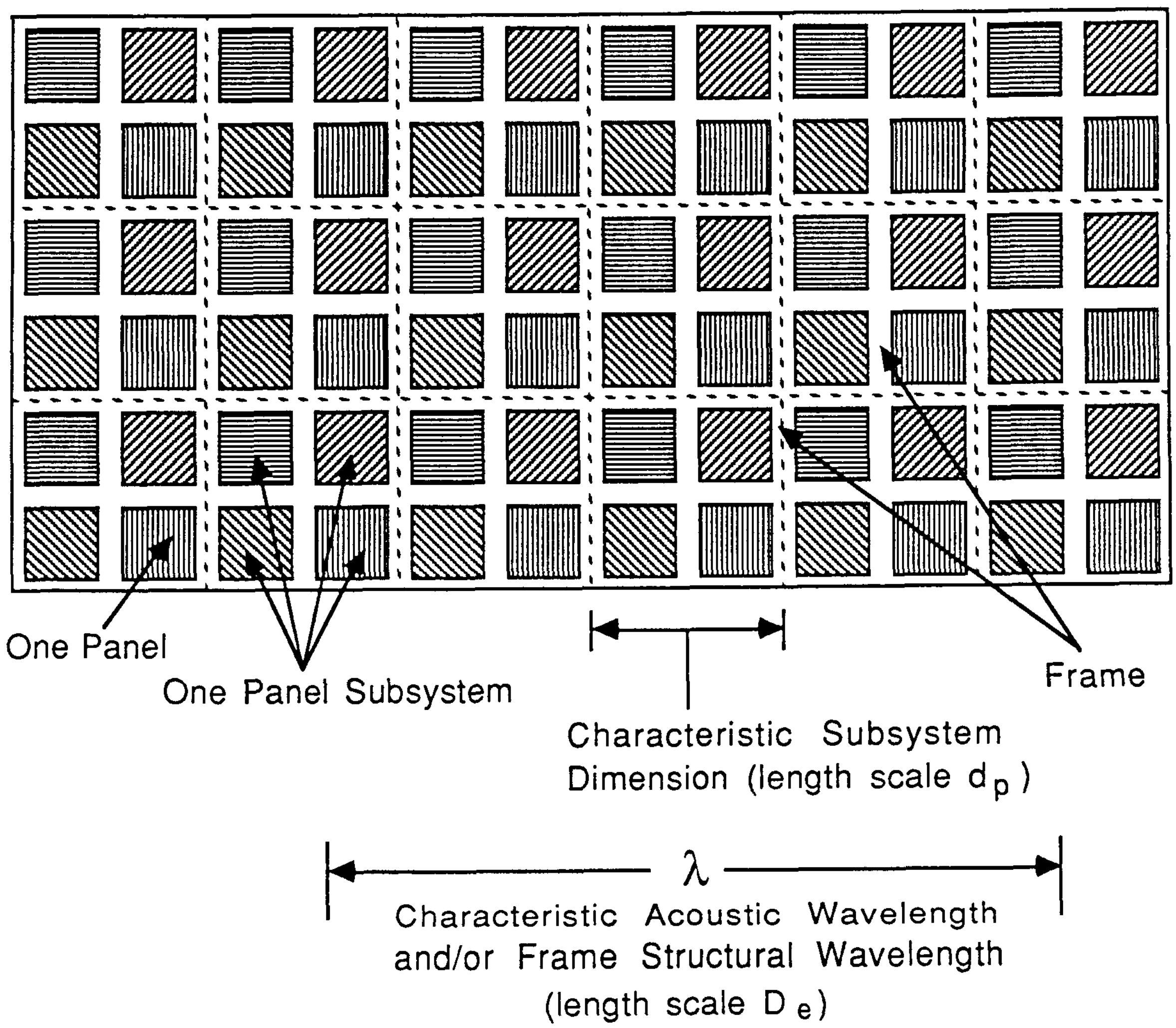
A new method is being developed to analyze low frequency sound transmission into panel/frame enclosures to facilitate the prediction of fuselage interior noise. The propeller noise associated with the advanced turboprop aircraft has given special importance to this problem. The new approach has broad application to panel/frame structures at relatively low frequencies and also provides a general analytical formulation for noise reduction concepts involving structural tuning. The coupled structural/acoustic problem is solved using a multiple scale perturbation expansion method, taking advantage of the scale separation between the panel size and the acoustic wavelength at low frequency.

Consider a panel/frame system forming the walls of an enclosure. Panel subsystems are attached to the frame to form a periodic structure. For a conventional aircraft wall with nominally identical panels, each subsystem would consist of only one panel. However, it is also possible to consider panel subsystems each containing several different panels. This more general arrangement, which is an important aspect of the present work, opens up new opportunities to develop noise reduction methods, e.g. ART. The acoustic wavelengths and the frame structural wavelengths are assumed large compared to the dimensions of a panel subsystem. Figure 2f-1 shows a typical panel/frame system.

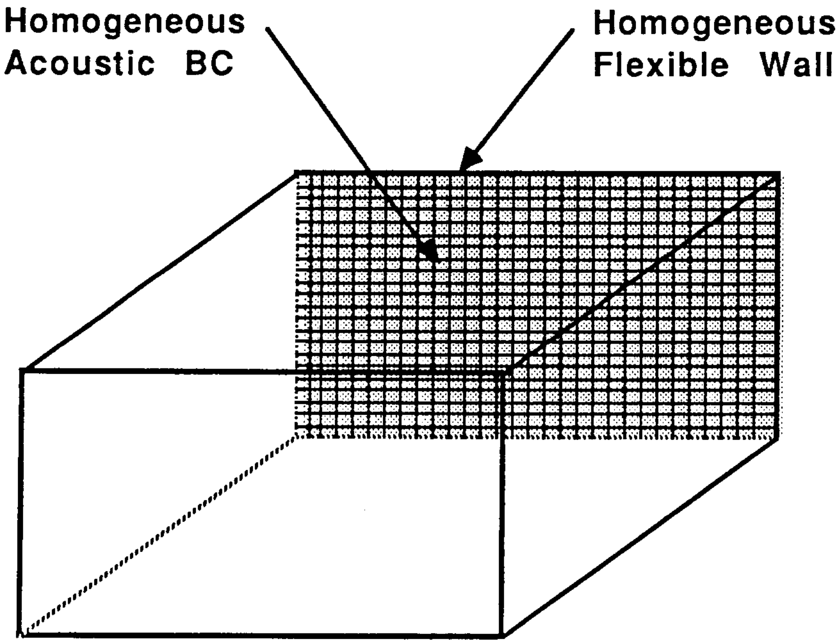
The overall solution can be thought of as being divided into a smoothed global solution and a local solution. The global solution is effectively smoothed over the panel length scale and depends only on the slow variables to lowest order. The local solution, which accounts for the detailed panel structure, depends strongly on the fast variables, while being slowly modulated by a function of the slow variables.

In the smoothed global solution, shown in Figure 2f-2, the frame structure and the boundary of the acoustic field are homogenized to form a continuous system. Essentially, the fine scale variations along the panel subsystems are not seen to lowest order, and the effects of the panel subsystems appear only in an average sense through transfer functions for distributed frame loadings and distributed acoustic boundary conditions.

The local problem is illustrated in Figure 2f-3. The lowest order local solution for subsystem motion corresponds to solving the problem of an infinitely periodic wall of identical panel subsystems subject to uniform frame displacement and uniform applied pressure differential. Gradients in the pressure differential and the frame displacement do not appear in the lowest order local solution. The wave equation reduces to Laplace's equation in this local region, with the main effect being the hydrodynamic inertial loading induced by the panel motion which effectively adds an apparent mass loading to the panels.



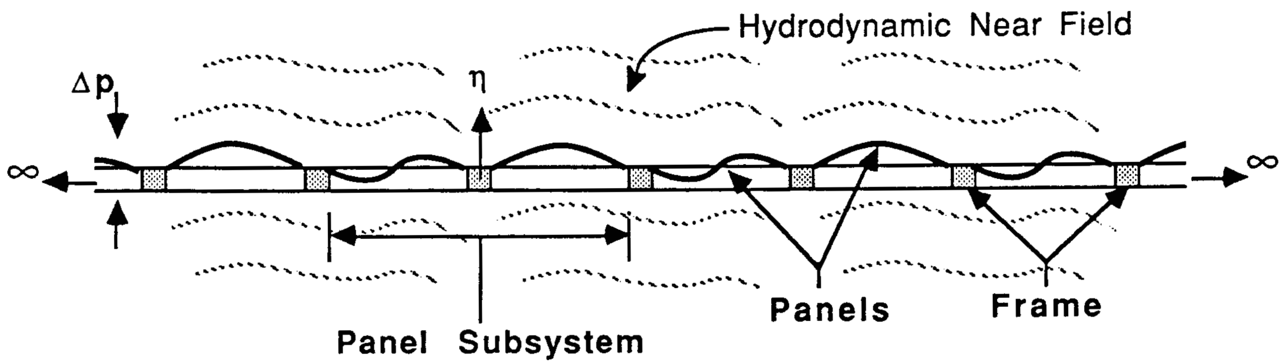
<u>**FIGURE 2f-1 PANEL/FRAME SYSTEM**</u>



For acoustic wavelengths and wall frame wavelengths large compared to the panel subsystem, the wall dynamics and the acoustic boundary condition can be modeled as a homogeneous system.

The dynamics of the panel subsystems are built into the equations of motion on the equivalent homogeneous wall and into the acoustic boundary condition using information from the local solution.

FIGURE 2f-2 SMOOTHED GLOBAL SOLUTION



Background Δp appears uniform across frame/panel system.

Frame motion η appears uniform.

Frame/panel structure appears to repeat periodically to $\pm\infty$.

FIGURE 2f-3 LOCAL SOLUTION FOR PANEL MOTION

The dynamics of the individual panels in a subsystem are governed by the appropriate structural model, which may be solved without further imposed limitations or restrictions for the general dynamic motion of these panels. The panel dynamics and acoustics, determined by the local solution, provide the transfer functions that appear as coefficients in the smoothed global analysis.

The multiple scale perturbation method provides a means to analyze low frequency sound transmission through panel/frame structures, even if the dynamics of the panel subsystems are quite complex. The main restriction inherent in the method is that the acoustic and structural frame wavelengths be large compared to the panel length scale. However, the formal development of a perturbation expansion method for this problem allows extension to higher order, thereby relaxing the severity of this requirement.

The approach has several potential advantages:

- The smoothed global (large scale) and local (fine scale) problems are separated and solved sequentially in a way that simplifies the overall problem and provides good physical insight.
- The method is computationally simple and efficient in comparison to detailed analysis of the entire system at low frequency, say by full modal or finite element analysis.
- There are no restrictions on the dynamics of individual panels, full panel dynamics being contained within the transfer functions. In particular, panel and frame resonances can lie in the same frequency range.
- The general problem of reducing sound transmission to the interior can be shown to involve the favorable choice of wall transfer functions derived in the local problem. The method suggests novel means of blocking sound transmission. For example, the effectiveness of Alternate Resonance Tuning (ART), which involves tuning panels within the same subsystem to oscillate out of phase to cancel acoustic transmission, is evident as a consequence of this general treatment.
- As a possible practical extension of the method, the local solution transfer function can be found experimentally by an appropriate series of tests on an isolated panel subsystem. The global solution then provides the proper framework in which to use these experimental results.

SECTION 3. EXPERIMENTAL EFFORT

Experimental work continues on the Alternate Resonance Tuning concept. Below is a summary of the current projects.

Section 3a. New Data Acquisition System

Work Update:

The LabVIEW portion of the data acquisition system is up and working. Additional memory was added to the Macintosh II computer in the laboratory to facilitate spectral data collection and use of *Mathematica*, a symbolic manipulation program. Most of the major portions of a software spectrum analyzer are now complete to complement the external pressure field experiment data collection.

Section 3b. Two Dimensional ART Experiment Development

Work Update:

The new two dimensional ART experiment with applied external pressure field is about 90% complete. The entire speaker array of 16 loudspeakers is complete, as well as the two dimensional duct enclosure, as shown schematically in Figure 4. Most of the amplifier sections for driving the speakers are now complete and operational. An anechoic termination has been prepared for use in the first experiments. Work remains to be done on software portions of the frequency measuring system and phase delay control system. These portions of the system, outlined in the July, 1988 progress report, were originally constructed using electronic hardware. However, it was determined that an adequate degree of control could be more easily obtained using the LabVIEW software.

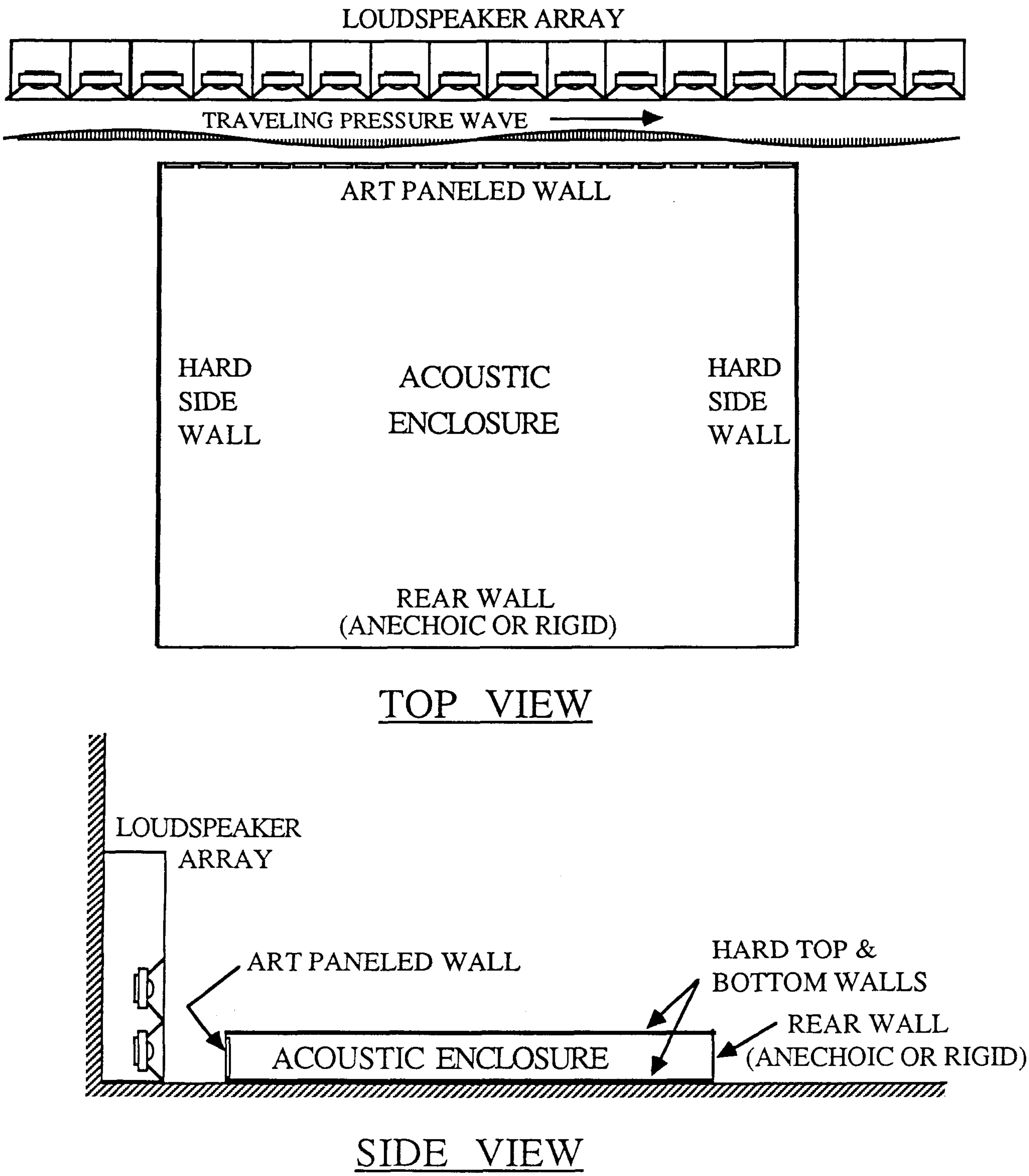


Figure 3b-1: Two dimensional ART Experiment showing loudspeaker array, ART paneled wall, and acoustic enclosure.

Section 3c. Double Panel Duct Experiments

The Dual Panel Wall experiments (DPW) are designed to explore the effect of a second wall on the performance of the Alternate Resonance Tuning concept. In this manner, it is possible to mimic the inner skin/outer skin construction of an airplane fuselage. As shown in Figure 3c-1, four panels are used in two walls of two panels each, placed in a duct which is effectively one-dimensional. One of the two-panel walls is placed near the sound source (upstream) with a coupling spacer to the downstream panel. Transmission loss data is then taken by placing one microphone just upstream of the first wall, a second microphone in the coupling duct, and a third microphone downstream of the wall setup. The termination impedance is anechoic.

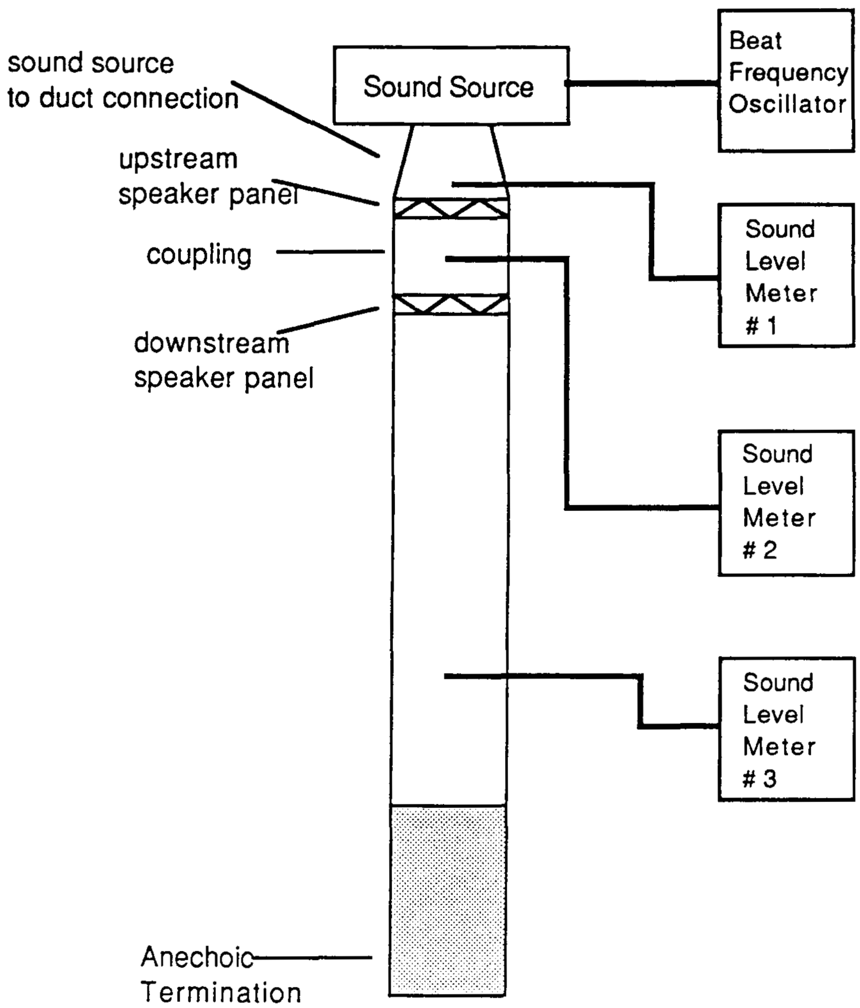


Figure 3c-1: Dual panel wall experimental apparatus showing the sound source, coupling between the upstream and downstream speaker panels, and microphone layout.

This apparatus allows for acquisition of transmission loss data across each individual wall, and across both walls simultaneously.

Since the last progress report, work has continued on the DPW experiments. Previous experiments had been conducted using three different coupling sizes: seven inches, two inches, and one inch. Next, a one-half inch coupler was used in the duct to determine the effect a very stiff air spring would have on the ART concept. Figure 3c-2 shows the transmission loss for four identical panels, each with a resonant frequency near 200 Hz, used with the one-half inch coupler. The curve closely resembles previous curves representing larger couplers with four identical panels in that the minimum transmission loss occurs at the resonance of the speakers. Absent on this curve is the transmission loss minimum associated with the coupling resonance. This additional resonance (due to the dynamics of the panels and the coupling duct air spring) is absent because the air spring in the coupler is much stiffer, moving the coupling resonance out beyond the frequency range of interest used in the experiment. Figure 3c-3 shows transmission loss when the downstream identical panels were replaced with ART panels (with resonances at approximately 100 and 300 Hz). These results were very similar to previous data with larger couplers. As expected, there are two minima near 100 Hz and 300 Hz. At the ART design frequency of 200 Hz, a transmission loss of 24 decibels was achieved. Figure 3c-4 gives the improvement in transmission loss (ART result minus identical panel result). This plot shows that the ART concept still works well, even in fairly confined spaces.

The next phase of the DPW experiment considered the simultaneous application of ART panels on both the interior and exterior walls. Using the same basic setup as in the earlier experiments, ART panels were placed on both ends of the seven-inch coupler. In the first experiment, ART panels of the same frequency were placed on the same side of the duct; effectively placing the ART panel pairs in series. Figure 3c-5 indicates that the use of two ART-panelled walls dramatically increases the transmission loss -- a maximum loss of 39 dB is achieved versus about 25 dB for single ART-panelled wall experiments. As before, there are the two minima associated with each panel resonance at 90 Hz and again at 270 Hz.

The position of the downstream ART panels was then reversed, resulting in a duct geometry where panels of the same resonant frequency were diagonally opposed. Figure 3c-6 shows that these results are similar to earlier experiments. The maximum transmission loss occurs at the design frequency of about 175 Hz, and the

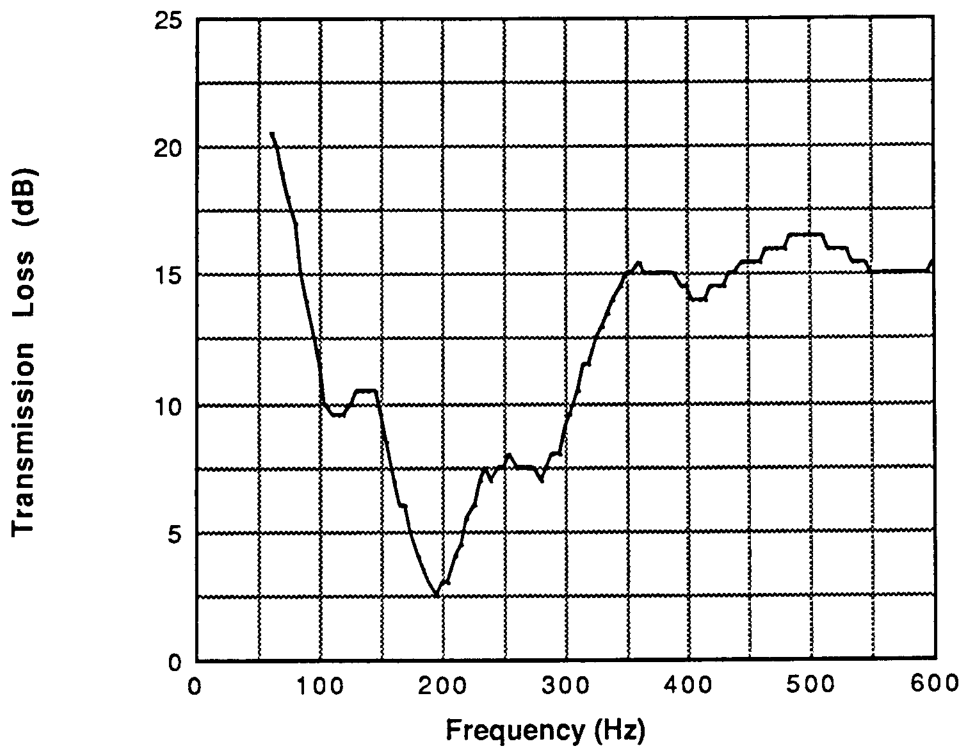


Figure 3c-2: Transmission loss results for four identical panels in the DPW experiments

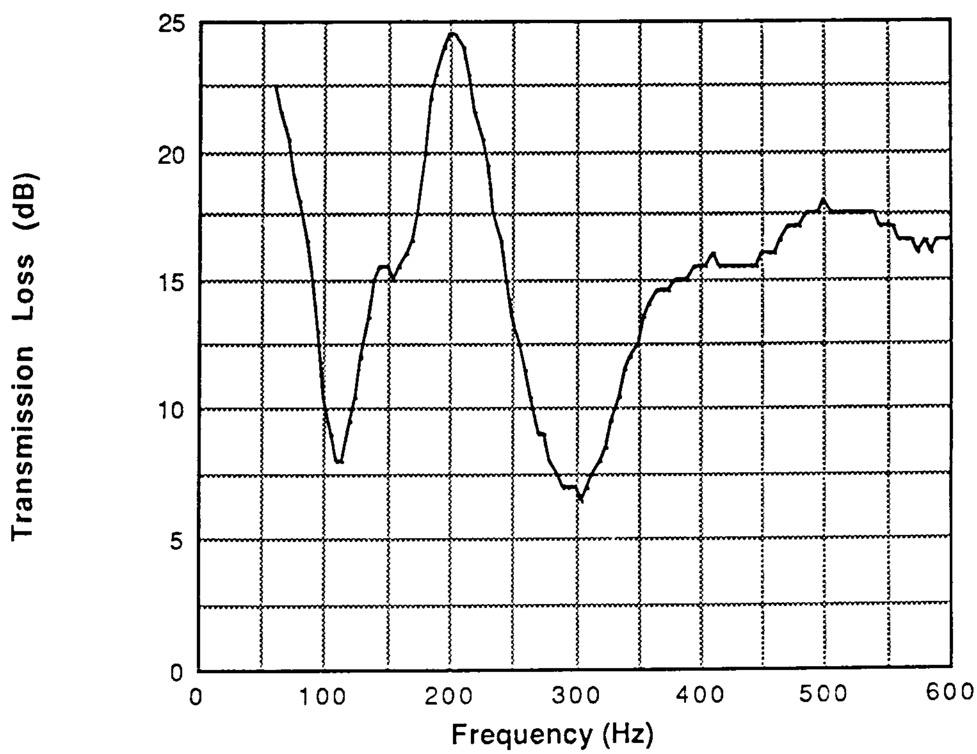


Figure 3c-3: Transmission loss for identical panels upstream and ART panels downstream.

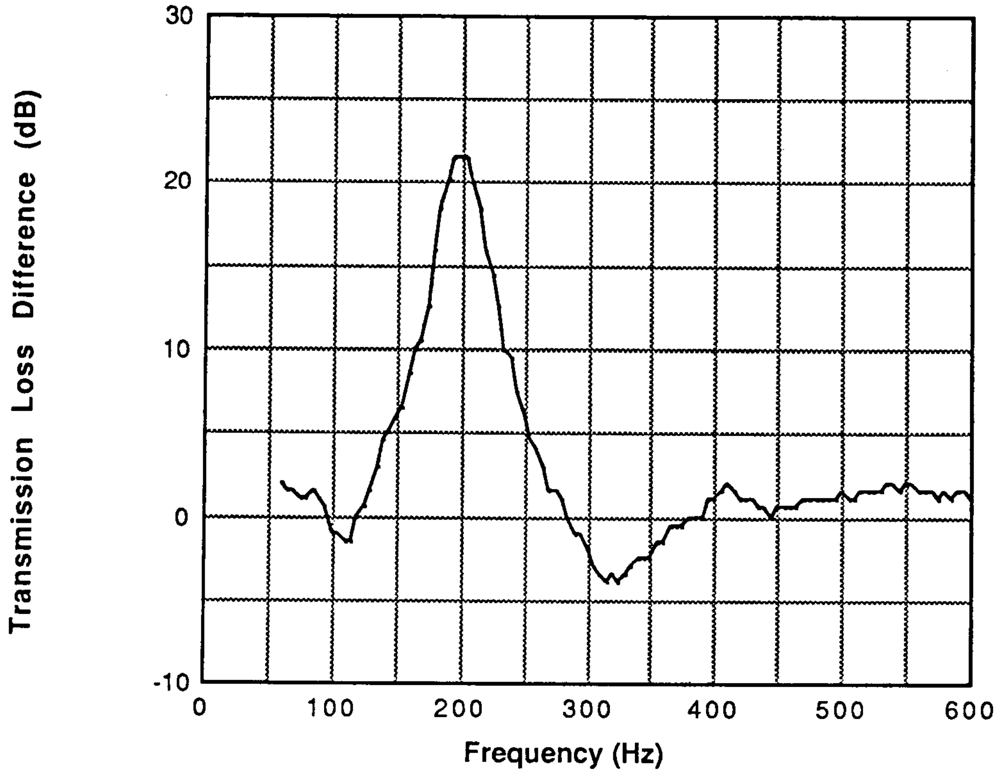


Figure 3c-4: Transmission loss difference between four identical panels and identical panels upstream

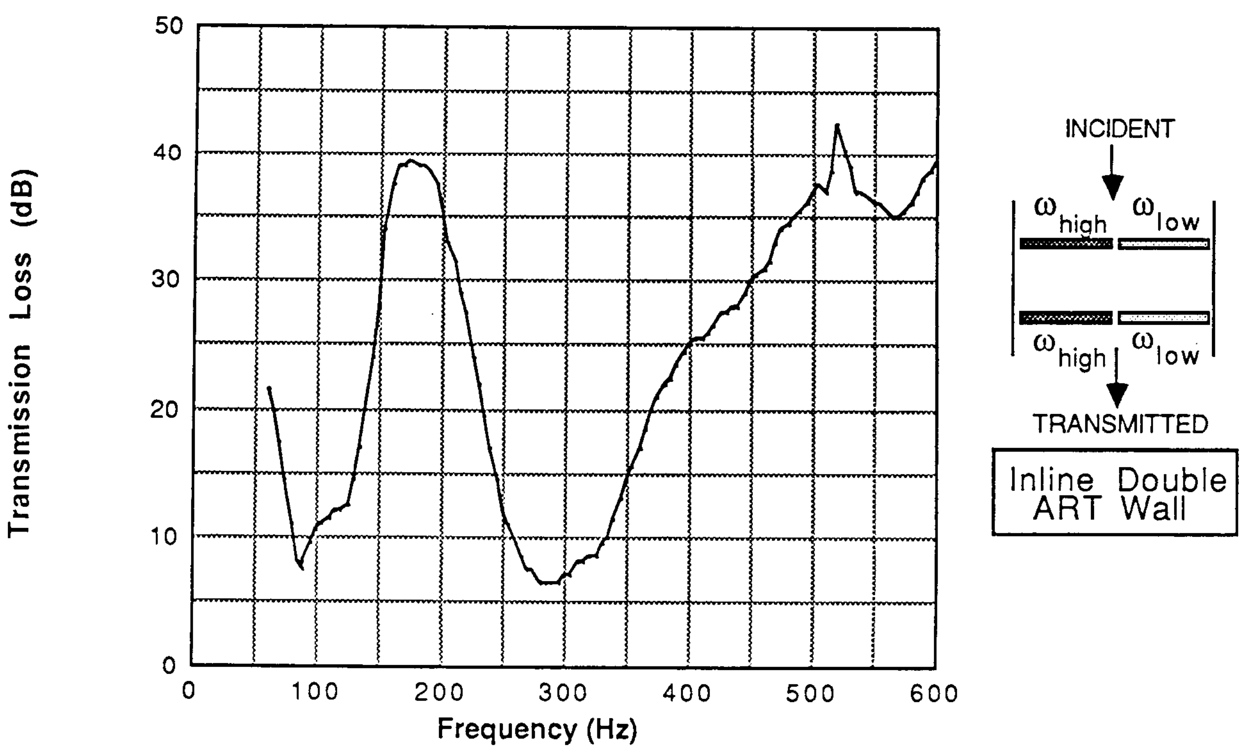


Figure 3c-5: Transmission Loss from Inline Double ART Wall with 7" coupler.

minima occur at the panel resonant frequencies of 90 and 270 Hz. While the maximum transmission loss is about 48 decibels, the bandwidth at the peak transmission loss frequency is narrow. However, the effective bandwidth at a transmission loss of ~ 40 dB is comparable to the ART speakers placed in series as shown in Figure 3c-5. Figure 3c-7 shows both of the dual ART wall experiments using the seven-inch coupler. The results are nearly identical except for the peak value of transmission loss. The difference in peak transmission loss occurs because in the parallel setup (less transmission loss), the downstream panel is in phase at all times with the panel directly upstream of it. In the reversed setup, the downstream panel is out of phase with the upstream panel in the maximum cancellation frequency range, improving the cancellation. This results in an additional 9 dB loss in the reversed setup.

The dual ART-panelled wall experiment was continued using the one-inch and one-half inch couplers. Figure 3c-8 shows the results for both the parallel and reversed cases using the one-inch coupler.The large decrease in transmission loss above the cancellation range (from about 350 Hz to 500 Hz) arises due to the aforementioned coupling resonance. There are several interesting features in this data which distinguish them from earlier experiments. Note that the transmission loss is significantly reduced in both cases compared to the results using the seven-inch coupler, and that the curve for the reversed case has shifted to the left. The decrease in transmission loss in the parallel case results from a stiffer air spring in the coupler; hence, the upstream and downstream panels operate together in the ART sense, and behave in part like a single panel wall rather than a double panel wall. In earlier experiments involving ART and non-ART panels, the upstream and downstream panel resonant frequencies were not the same, and the resulting panel interaction is different.

The changes in the reversed case transmission loss curve are due to a more complex phenomena. This data was taken using the one-inch coupler, where a smaller amount of air inside the coupler effectively stiffens the air spring between the panels. Since there are now four ART panels mounted to a very narrow coupler and panels with the same resonance are mounted diagonally to each other, the air inside the coupler is forced to move transversely (rather than back and forth with the panels) when the panels are not in phase. This results in an increase in the apparent mass of the panels, lowers the effective panel resonances, and shifts the transmission loss curve to a lower frequency domain. The narrow bandwidth prevents the maximum transmission loss at the design frequency from reaching the

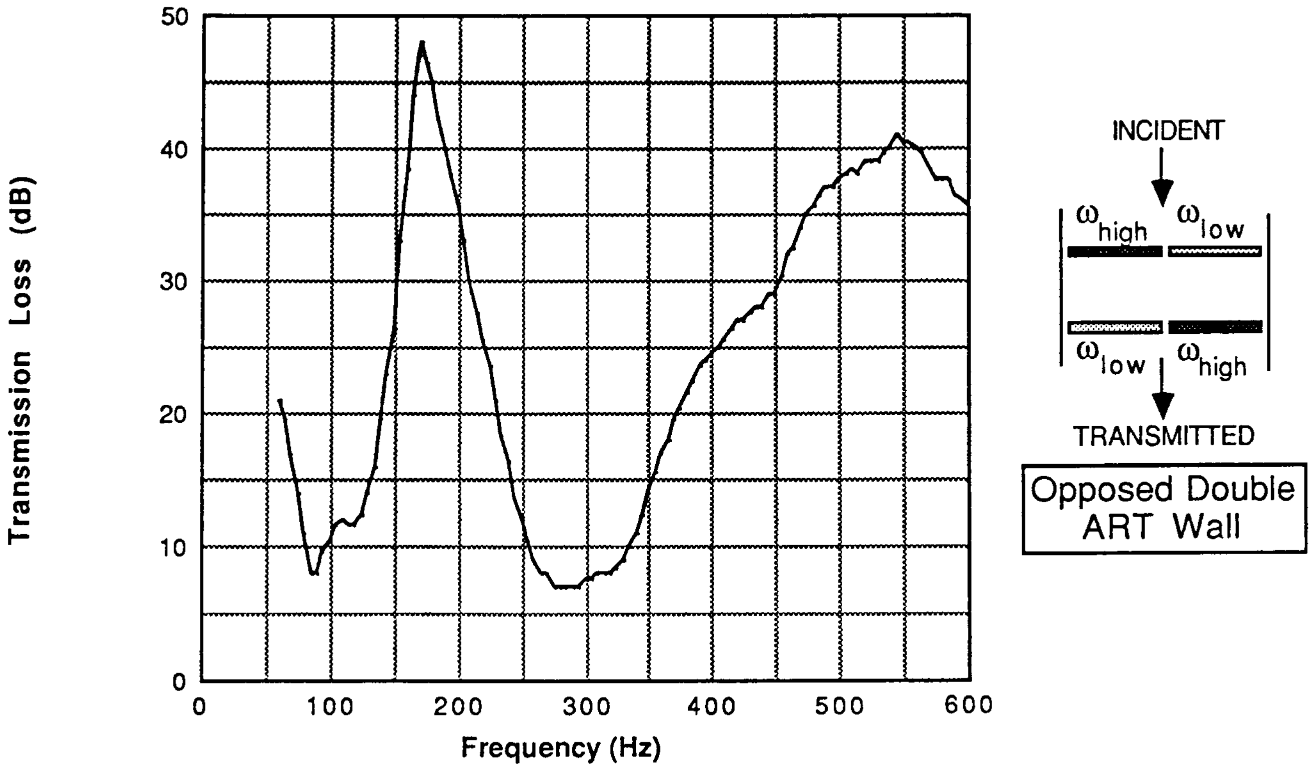


Figure 3c-6: Transmission Loss with Opposed Double ART Wall with the 7" coupler.

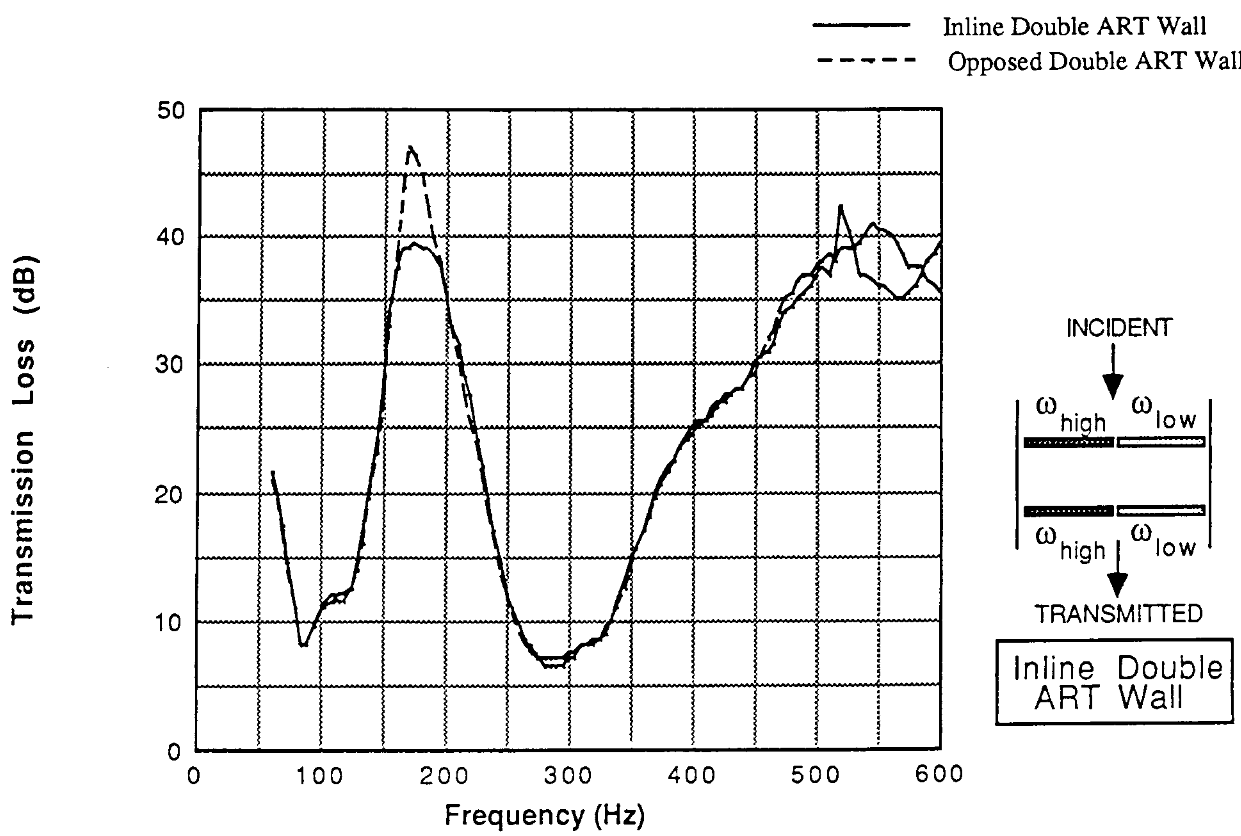


Figure 3c-7: Total Transmission Losses from Inline and Opposed Double ART Walls.

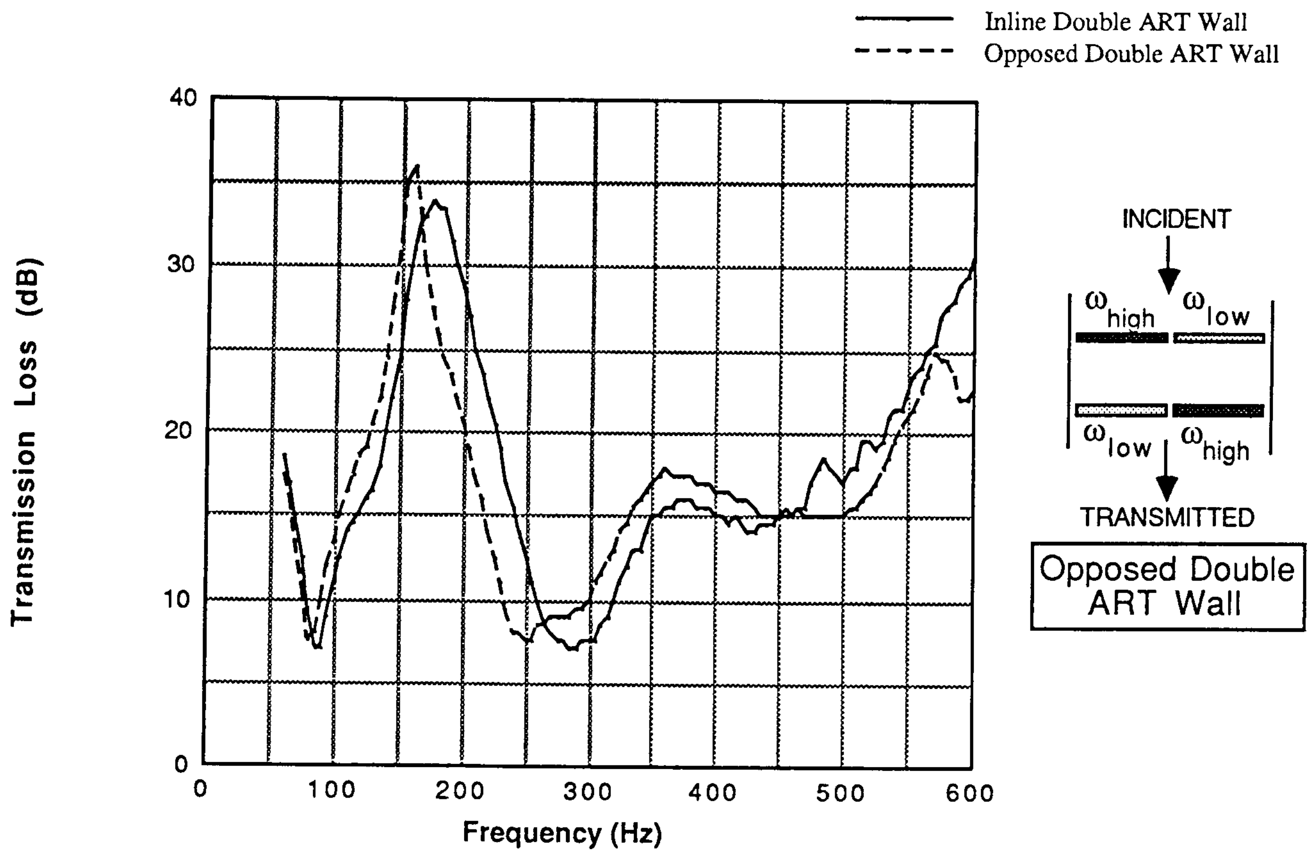


Figure 3c-8: Transmission Losses With Inline and Opposed ART Walls with the 1" coupler.

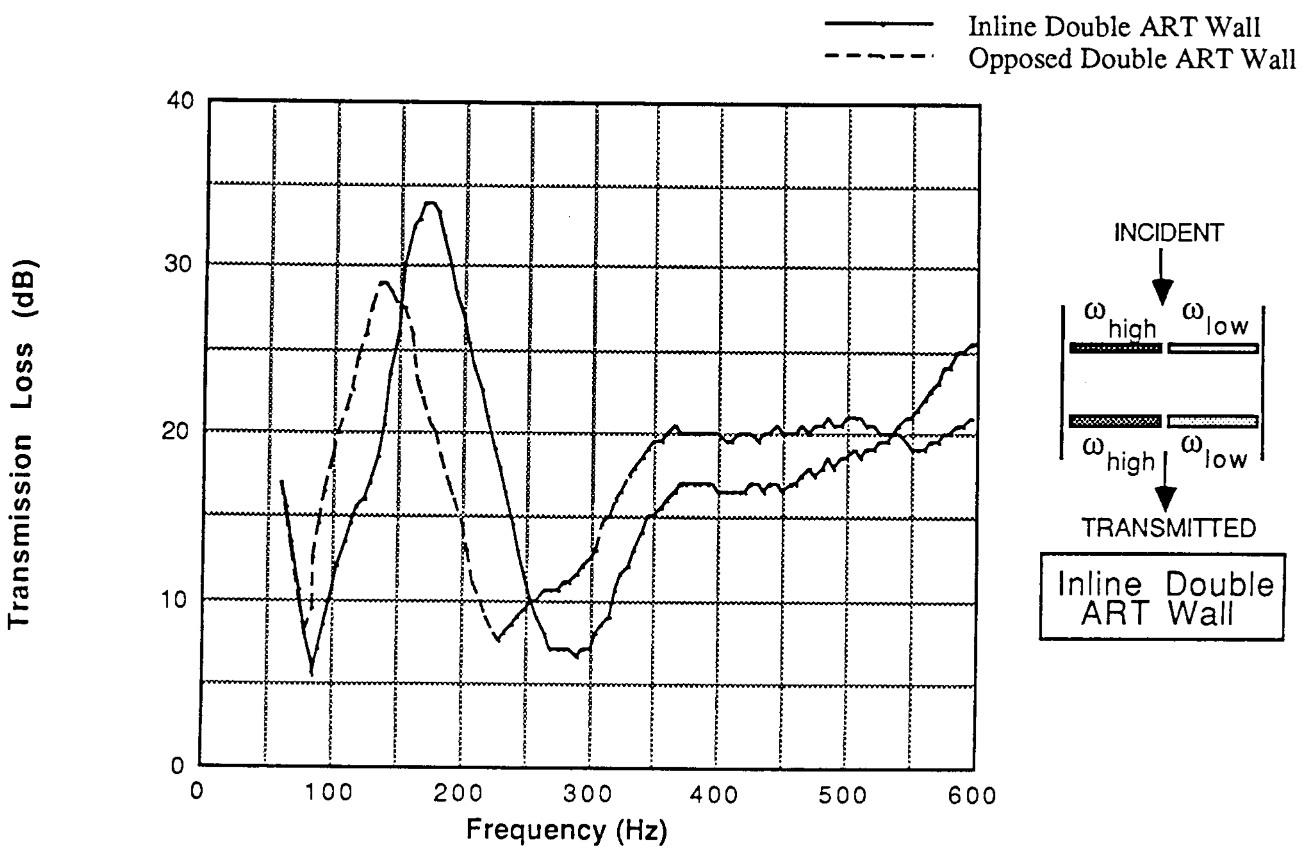


Figure 3c-9: Inline and Opposed Double Art Walls with the 1" coupler.

higher levels present in earlier experiments. Presumably if the panels in this case were retuned to regain the lost bandwidth, this case would then yield very good results.

ART-panelled wall experiments were then performed with the one-half inch coupler. The results of both the parallel and reversed cases are shown in Figure 3c-9. The phenomena discussed above for the one-inch coupler are present again in this data; the peak losses in both cases are reduced, and the data indicating transmission loss for the reversed case is shifted even more severely to lower frequencies than before, resulting in more significant transmission losses compared to the seven-inch coupler. Figure 3c-10 shows the transmission loss results for all three parallel panel cases (the seven, one, and one-half inch couplers), and Figure 3c-11 shows all three results for the reversed panel cases.

Future work on the dual-panel wall experiments will examine the use of one large panel (representing larger panels on the fuselage outer skin) in conjunction with a second wall of two or four ART panels representing the smaller tuned panels inside the fuselage. Another interesting configuration that might be pursued in the future would be the use of double ART walls with the panels in one wall tuned to cancel in a different band from the panels on the other wall.

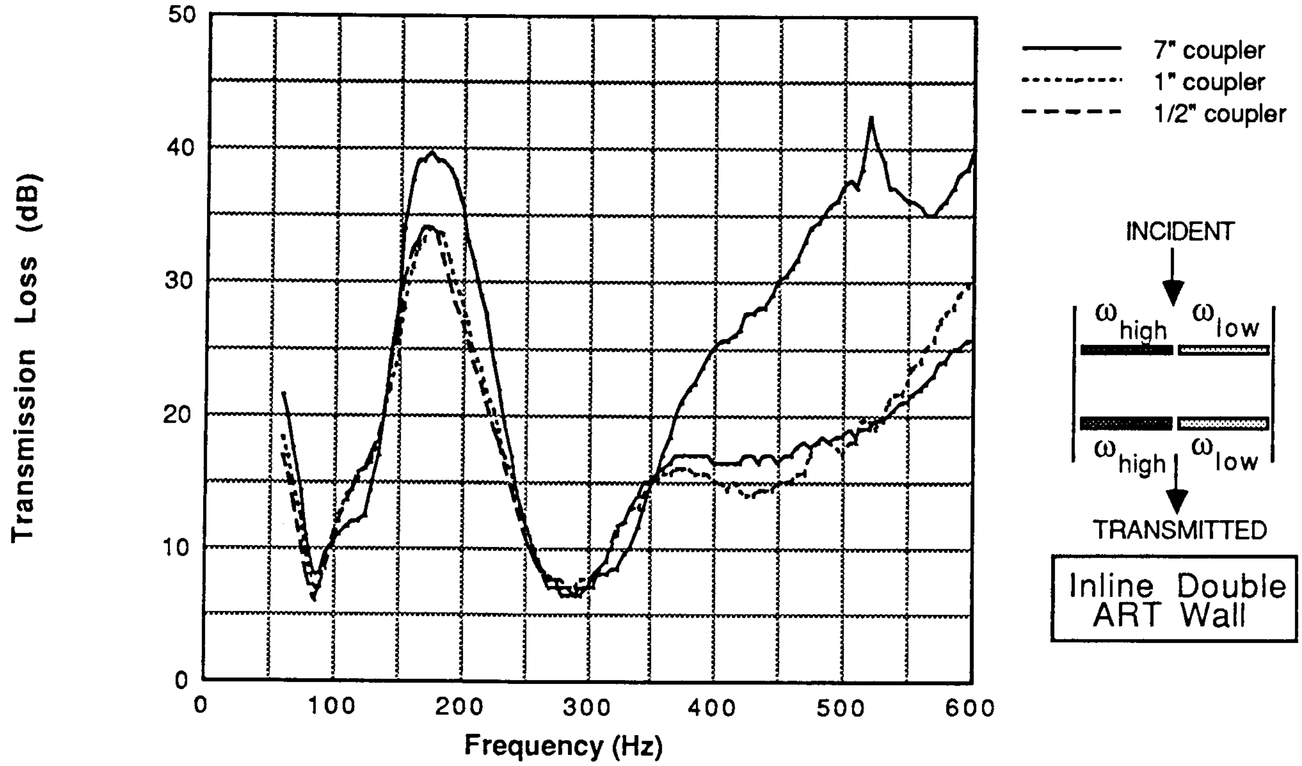


Figure 3c-10: Transmission Losses from all Inline Double ART Walls.

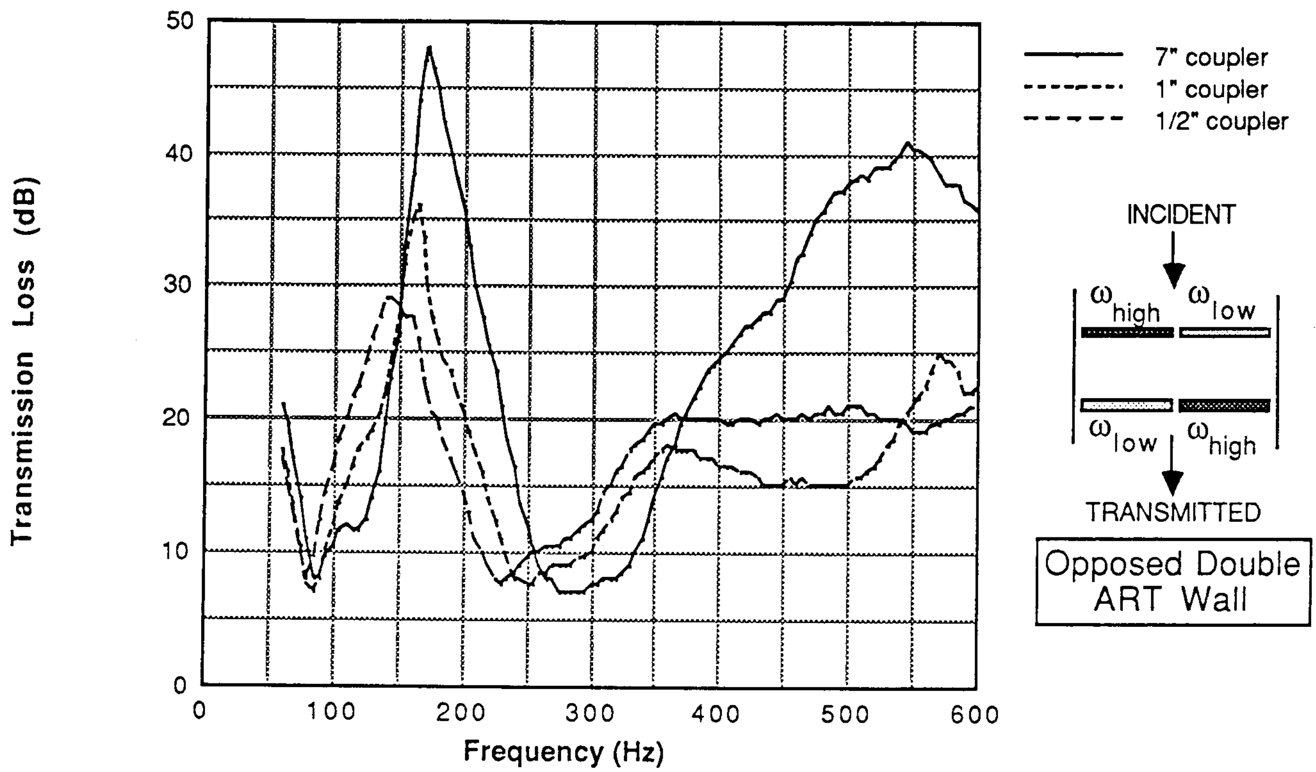


Figure 3c-11: Transmission Losses from all Opposed Double ART Wall Experiments.